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*Influence of the Amazon River Outflow on
the Ecology of the Western Tropical Atlantic
I. Hydrography and Nutrient Chemistry*¹

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ABSTRACT

The influence of the Amazon River discharge on the nutrient chemistry and biological productivity in the western tropical Atlantic and the eastern Caribbean was investigated during two oceanographic cruises in the fall of 1964 and the spring of 1965, respectively. The river outflow is entrained in the Guiana Current and carried to the north and east, affecting an area that is at times a million square miles, as indicated by surface salinity. The effect is greater during the South American rainy season (spring-summer) than during the dry season (fall-winter), in terms of both total area influenced and the degree of freshening of the surface water. On both cruises, a large lens of appreciably freshened surface water (200–300 miles in diameter) was encountered several hundred miles to the north and east of the Amazon estuary and separated from it by water of higher salinity.

In the surface water influenced by the Amazon River compared with the surrounding seawater, the concentrations of nitrate, phosphate, and phytoplanktonic organisms were lower while the levels of silicate were appreciably higher. The direct over-all effect of the river, therefore, is to decrease the fertility of the ocean into which it flows. However, a region of high biological activity was encountered in the Guiana Current between the coast of the Guianas and the above-mentioned lens of freshened surface water. This resulted from geostrophic uptilting of water in that region, bringing nutrient-rich subsurface water into the euphotic layer; possibly this was caused or enhanced by the weight of the accumulated river water offshore.

Introduction. The Amazon River discharge averages some 2×10^5 cubic meters of water per second—five times that of the Congo, the world's second largest river, twelve times that of the Mississippi, and approximately 18% of the total river discharge in the world (Davis 1964). Judging from river-gauge data (Oltman et al. 1964), the Amazon River height (and hence its discharge)

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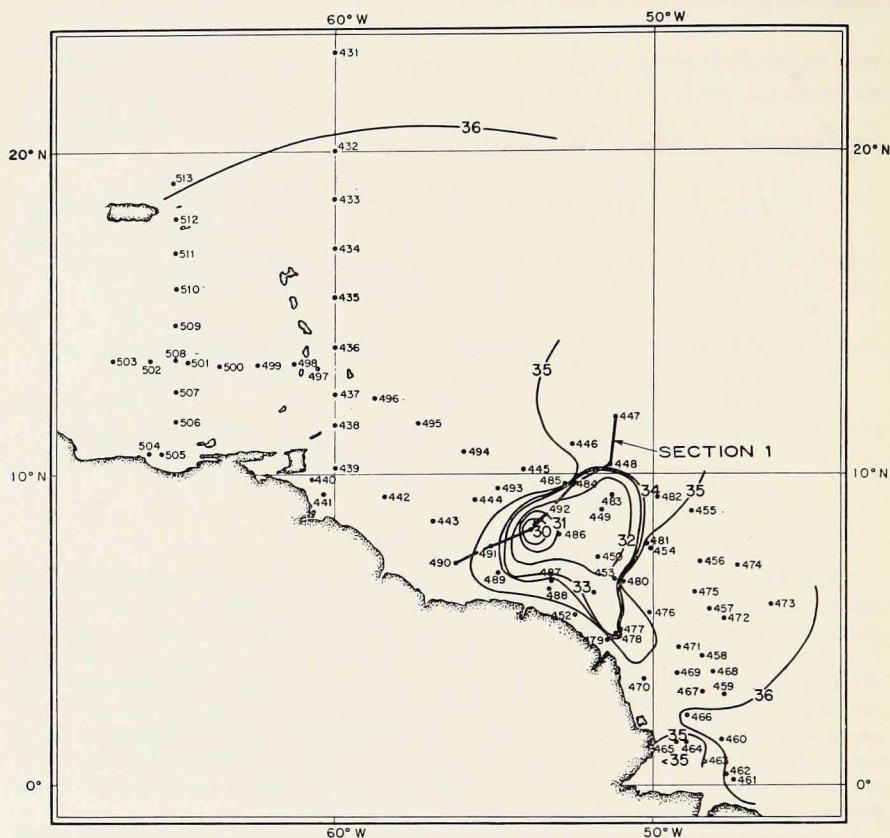


Figure 1. Station positions and surface salinity contours for ATLANTIS II Cruise 14 (October-December 1964).

varies seasonally between the wet (spring-summer) and dry (fall-winter) seasons by as much as two-fold.

If the Amazon discharged its fresh water into a quiescent ocean where it could accumulate undisturbed over long periods of time, its influence would be marked and obvious. For example, it could cover in one year the entire Mediterranean Sea with a layer of fresh water some 3 m deep. However, the Amazon flows into the strong Guiana Current—the extension of the South Equatorial Current, which flows in a northwesterly direction along the South American coast from Cape San Roque into the Caribbean. Thus, the river water is rapidly mixed with high-salinity water of that current system and may be transported for considerable distances to the north. Even so, its influence may be readily detected by reduced salinities at the sea surface, the geographical extent of which will be discussed below.

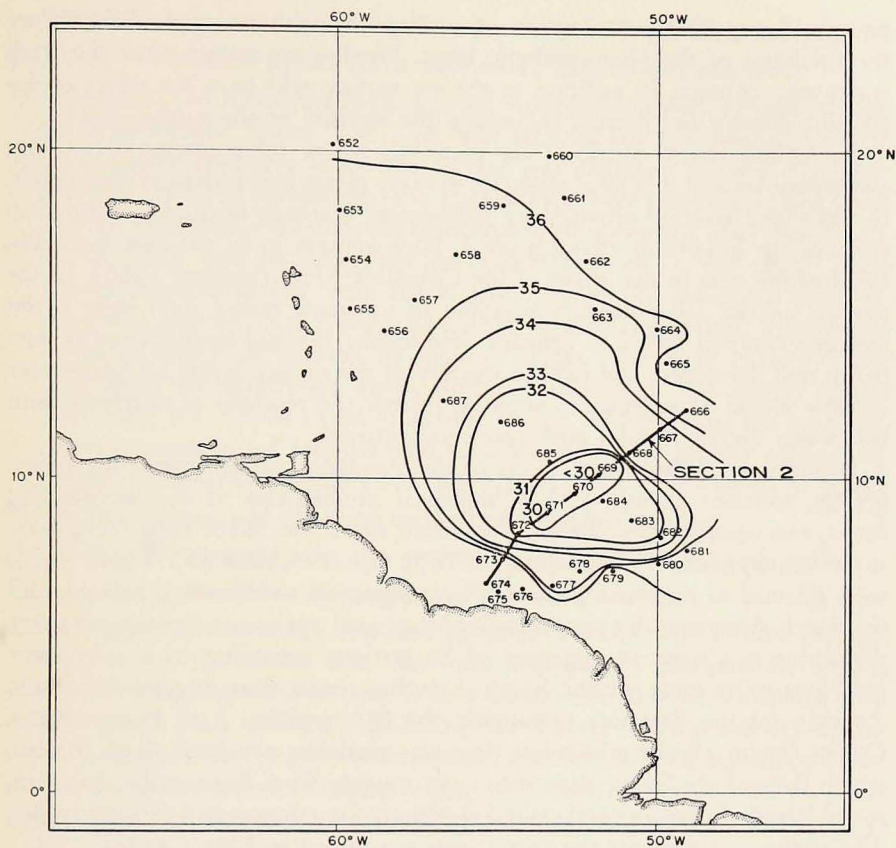


Figure 2. Station positions and surface salinity contours for CHAIN Cruise 48 (May-June 1965).

However, the size of the area that is measurably freshened by the Amazon River is in itself a subject of academic interest. What is of greater significance, biologically, is the extent to which the fresh-water runoff may affect or influence the organic productivity of the ocean. Since there is a tendency for the fresh water to remain at or near the sea surface, its influence can be expected to occur primarily in the euphotic layers within which the production of organic matter takes place.

There are several ways in which river discharge might influence biological productivity in the sea. If essential dissolved plant nutrients (nitrate, phosphate, silicate, etc.) are entrained in the river water, they would be expected to enhance the growth of planktonic algae, or conversely, if unusually poor in nutrients, to dilute those normally present in the sea surface and decrease biological production. If the river water is rich in clay minerals or other inorganic suspended solids or if it is highly colored by dissolved organic com-

pounds, the resulting attenuation of sunlight by such material could reduce the thickness of the photosynthetic layer. Finally, no matter what the fresh water may contain, its addition to the sea surface will have the effect of decreasing density and thereby increasing the stability of the surface layer.

In regions where nutrients are plentiful, where solar energy is limiting, and where vertical mixing is adequate to carry plants below their critical depth, the increased stability provided by fresh-water drainage might be expected to enhance the growth of phytoplankton. Such appears to be the case at certain times of the year in the offing of the Columbia River (Hobson 1966). In the tropics, on the other hand, the supply of nutrients rather than light is the common limiting factor to primary production; thermal stratification is normally well developed, and further stability of the surface layers by fresh-water outflow would be expected to suppress further the resupply of nutrients from below and thereby inhibit phytoplanktonic growth.

In order to evaluate the effects of the Amazon outflow upon the hydrography, nutrient chemistry, and biological productivity of the surrounding ocean, two oceanographic cruises were made, one in the fall of 1964 (ATLANTIS II Cruise 14) and one in the spring of 1965 (CHAIN Cruise 48). These cruises were planned to provide a picture of oceanographic conditions associated with the South American dry season (fall-winter) and wet season (spring-summer). ATLANTIS II Cruise 14 consisted of 82 stations extending in a band some 300-400 miles wide off the South American coast from the mouth of the Amazon (at the Equator) to roughly the 65° meridian (i.e., Puerto Rico). CHAIN Cruise 48, for which less time was available, consisted of 38 stations, which covered the South American coast roughly from Paramaribo, Surinam, to the Island of Barbados and extended offshore for a distance of 500-600 miles. The station positions for the two cruises are shown in Figs. 1 and 2.

The cruises had two basic purposes: (i) to determine and describe the size and location of the geographical area influenced by the Amazon River, and (ii) to determine the nature and levels of chemical nutrients and planktonic populations within that area. The present report considers the geographical area affected by the Amazon River and its nutrient chemistry. Succeeding reports will consider the populations of phytoplankton and zooplankton in the region.

Methods. Water samples were collected with Nansen bottles from pre-selected depths at all standard hydrographic stations. On CHAIN 48 these observations were augmented by hourly surface bucket samples taken while the ship was in motion. All measurements on ATLANTIS II-14 were made on board as soon as possible after collection, with the exception of iron and particulate phosphorus. Samples collected on CHAIN 48 were stored frozen in 500-ml plastic bottles, unless otherwise indicated; they were analyzed upon return to the laboratory. Earlier work (Ketchum et al. 1958) has confirmed the fact that results are not altered significantly by the freezing process.

The following methods were used in the analysis of individual components:

SALINITY: A Hytech Model 6210 Laboratory Salinometer was used.

PHOSPHORUS: ON ATLANTIS II-14, 200-ml water samples were filtered through 0.8μ membrane filters. The filter was retained for the determination of particulate phosphorus while the filtrate was analyzed for both inorganic and total dissolved phosphorus. ON CHAIN 48, where particulate phosphorus was not measured, the results are expressed as inorganic and total phosphorus, in the latter case including the particulate fraction in the total. These separate determinations were made according to the following methods: inorganic, Murphy and Riley (1962); total and total dissolved, Menzel and Corwin (1965); particulate, by ignition of the filter in a 125-ml Vycor flask using an oxygen-gas flame, further oxidation of the organic matter with 0.4 g $K_2S_2O_8$ in 15 ml of distilled water, refiltration of the sample to remove uncombusted residues, and subsequent analysis for the released inorganic phosphorus (Murphy and Riley 1962) in a final volume of 60 ml.

NITRATE: Determined after the method of Grasshoff (1963).

AMMONIA: Determined after the method of Richards and Kletsch (1964).

SILICA: Determined after the method of Grasshoff (1964).

IRON: ON ATLANTIS II-14, measured volumes of water were filtered through 0.8μ membrane filters. The filter was subsequently analyzed for ferrous ion following digestion at $120^\circ C$ in a steam autoclave in a solution containing 1% HCL and 2.5% $K_2S_2O_8$. The filtrate was digested in a similar manner, and both fractions were measured colorimetrically according to the method of Lewis and Goldberg (1954). ON CHAIN 48, only total iron was measured. All liquid samples were stored in plastic bottles containing, in final solution, 1% HCL.

Oceanic Distribution of the Fresh-water Drainage. The METEOR Atlas, showing the monthly distribution of surface salinity in the Atlantic (Böhnecke 1936), depicts a broad band of relatively fresh surface water ($< 36\text{‰}$) between about $15^\circ N$ and $5^\circ S$ and extending across the entire ocean. However, the more recent IGY cruises (Fuglister 1960) have clearly shown, in profiles along $16^\circ N$, $8^\circ N$, and the Equator, the presence of a large midoceanic region of high surface salinity ($> 36\text{‰}$). The same profiles have also made it clear that the low salinity on the eastern side of the Atlantic is several hundred meters deep and results from the upwelling of subsurface water along the African coast. On the other hand, the water on the western side of the tropical Atlantic consists of a layer that is no more than about 50 m deep; this overlies higher-salinity water ($36\text{--}37\text{‰}$).

Thus the origin of the two regions of low surface salinity on either side of the Atlantic is different and the regions are not contiguous. It is our contention that the freshened water in the western tropical Atlantic represents runoff

from the Amazon River system, including other fresh-water drainage from northern South America. Other sources are probably of minor importance. Runoff from the Orinoco, the only other major river in the region, apparently flows mostly to the northwest through the Gulf of Paria and into the Caribbean; therefore it does not contribute appreciably to the freshening of the Atlantic east of the Windward Islands (van Andel and Postma 1954).

For the sake of discussion and exposition, the area influenced by fresh-water runoff will be considered to be that within which surface salinities are less than 36‰ . This criterion is used because there appears to be no oceanic surface water in the tropical or semitropical Atlantic having a salinity below 36‰ except for that produced by upwelling along the eastern Atlantic (see above) and in the region under discussion here.

The METEOR Atlas (Böhnecke 1936) also shows the geographical pattern of the Amazon River outflow month by month throughout the year. Again, however, the picture has been generalized and idealized and is not entirely consistent with the data. For that reason, the data, which have been replotted for the region bounded by 0° – 20° N and 40° – 60° W, are reproduced in Fig. 3. The contours outlining the distribution of surface salinities of 36‰ are shown for each month of the year. When they occur, salinities of 33‰ and 30‰ are also contoured. For most months, the envelope of salinities of less than 36‰ extends farther east than 40° W, and its boundary is therefore not illustrated. It may be estimated, however, that the area so enclosed varies in size from less than 250,000 square miles in January-February to over a million square miles in late spring and summer.

Although this area is irregular in shape, it most closely resembles an ellipse whose center is located near 10° N, 50° W and whose long axis lies in a north-west-southeast direction. Characteristically, a tongue of high-salinity water intrudes from the southeast close to the shore along the coast of South America almost to the Amazon estuary. This is the Guiana Current, which subsequently entrains the Amazon outflow and carries it to the north and west along the coast and, during the wet season, well into the Caribbean. Beginning late in spring the tongue of freshened water begins to spread southeastward from its center, forming the southeastern half of the ellipse. This is presumably carried by the Equatorial Countercurrent which, according to Defant (1961), has its origin near 10° N, 50° W and is most strongly developed in summer. Thus the fresh water is carried in two opposite directions; (i) by the Guiana Current to the northwest, and (ii) by the Equatorial Countercurrent to the southeast, producing an elliptical pattern of a size that varies seasonally depending upon the volume of the river discharge and the strength of the respective current systems. This description is greatly simplified and neglects other minor components of the surface circulation that may be important at certain times of the year. A more detailed discussion of this circulation has been given by Cochrane (1963).

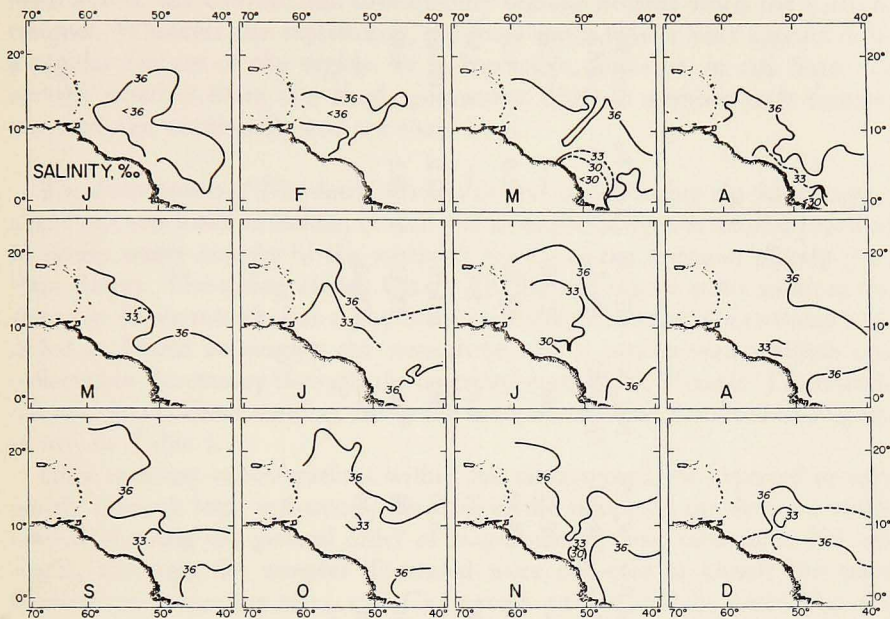


Figure 3. Monthly surface salinities (‰) between 0° – 20° N and 45° – 60° W plotted from the METEOR Atlas (Böhnecke 1936).

The distribution of surface salinity obtained during the two Woods Hole cruises agrees in general with the METEOR Atlas data (Fig. 3), but it also shows some interesting additional features (Figs. 1 and 2). With the exception of the Amazon estuary itself (sampled during the fall but not during the spring), the lowest salinities were observed at the center of a lens of freshened water centered around 8° – 10° N and 50° – 55° W, some 500 miles or more northwest of the river mouth and 100–200 miles offshore. The fact that this fresh-water lens is isolated from the Amazon estuary was well established during the spring cruise, when surface samples were collected each hour on the section across its southern edge (i.e., between Sts. 674 and 681). No salinities below 32° ‰ were observed along that section, although values as low as 24° ‰ were encountered in the center of the lens 100 miles or more to the north.

The origin of this fresh-water lens is not clear. It appears that the main body of the Guiana Current flows inside it, along the coast, and that it represents an offshore eddy between the Guiana Current and the southern edge of the North Equatorial Current. But how the freshened water crosses the main body of the strong coastal Guiana Current is not known. Possibly the latter ceases to flow at times due to a slackening or temporary reversal of the local wind system, allowing a bubble or bubbles of river water to cross the

Table I. Surface chemistry of the Amazon River discharge.

Cruise	Date	Station	Sal. (‰)	PO ₄ -P (μg/L)	Total P (μg/L)	NO ₃ -N (μg/L)	NH ₄ -N (μg/L)	SiO ₃ -Si (μg/L)	Diss. Fe (μg/L)	Part. Fe (μg/L)
ATLANTIS II-14	11 Nov 64	Estuary*	14.00	0.15	—	0.12	2.00	21.66	—	252.56
CRAWFORD 125	15 Jun 65	Estuary*	6.95	0.48	0.51	9.28	—	63.72	12.3	3.54
ATLANTIS II-14	11 Nov 64	461†	36.26	0.07	0.30	0.14	2.65	2.42	—	3.54
ATLANTIS II-14	15 Nov 64	465**	12.87	—	4.16	5.30	4.90	83.76	81.0	3337.40
ATLANTIS II-14	26 Nov 64	492††	29.46	0.01	0.16	0.08	0.25	18.47	20.1	4.42
CHAIN 48	1 Jun 65	669††	24.84	0.03	0.18	0.14	—	13.50	—	—

* Approximately 50 miles up the Para River.

† Fifty miles NE of river mouth.

** Fifty miles NW of river mouth.

†† Center of "fresh water" lens, 600 miles NW of river mouth.

main axis of the Current and subsequently become isolated when the Current resumes. Whatever the explanation, the fresh-water lens or eddy appears to be a regular feature of the region. It is impossible, however, to tell from our surveys whether there is a single permanent eddy or whether such features are produced continually and are short lived.

The Distribution of Nutrients. On ATLANTIS II-14, during the fall of 1964, a port call was made at Belem, Brazil, and an opportunity was thereby provided to obtain water samples in the southern branch of the Amazon estuary (i.e., Para River). The spring cruise, CHAIN 48, did not extend as far south as the Amazon River mouth, but a physical oceanographic cruise, CRAWFORD 125, called at Belem at roughly the same time, and a surface-water sample was collected in the estuary through the cooperation of W. G. Metcalf. The chemical analyses of these samples, using the same methods as described above, are shown in Table I.

Since nutrient concentrations within the estuary could be expected to vary widely through local influences, the state of the tide, etc., the data are useful only in showing the general order of magnitude of these substances. For example, although the samples illustrated were collected at almost the same location on ATLANTIS II-14 and CRAWFORD 125, it will be noted that the salinity of the former was more than twice that of the latter.

The fall estuarine sample (ATLANTIS II-14) was low in both inorganic nitrogen and phosphorus and the spring sample (CRAWFORD 125) differed only by showing moderately high levels of nitrate. Silicate and particulate iron, on the other hand, appeared to be present at relatively high concentrations within the estuary.

The surface chemistry at St. 461, just 50 miles northeast of the river mouth, revealed a high salinity and a low nutrient concentration, indicating the absence of river water. Presumably these values are representative of the oceanic equatorial Guiana Current water before it entrains the river outflow. On the other hand, the surface water at St. 465, 100 miles downstream from St. 461, clearly included the river drainage, since the salinity was lower and the nutrient levels were as high as, or higher than, those found within the Para River estuary. Presumably the surface water at St. 465 included, and its chemistry was representative of, the drainage from the extremely broad and shallow northern branch of the Amazon estuary. Nitrogen and phosphorus levels were moderately but not exceedingly high at that location, silicate was somewhat higher, and particulate iron was an order of magnitude greater than that observed in the Para River. In general, no striking difference in nutrient level between spring and fall was observed, and the concentration of the essential nutrient compounds of nitrogen and phosphorus were not impressively high in the river drainage system, so far as could be seen from the data, at either time of year. This is consistent with the findings of Klinge and Ohle (1964),

who have reported extremely low levels of nitrogen and phosphorus in the waters of the Amazon River itself.

By the time the river water had reached the lens or eddy of low-salinity water shown in Figs. 1 and 2—a distance of some 600 miles from the river mouth—the concentrations of inorganic nitrogen and phosphorus were extremely low; in fact, they were no greater than, and were perhaps even lower than, those typical of tropical surface waters (Table I). Particulate iron, which was so high near the river mouth, decreased by almost a thousand-fold, but this was almost certainly due to sedimentation of the particulate matter. In contrast to the turbid water within the estuary and near the river mouth, the water in the offshore fresh-water region was extremely clear and almost devoid of suspended solids, though it retained a characteristic brownish-black discoloration. The only chemical indicator that confirmed the Amazonian origin of the fresh-water lenses centered at St. 492 (*ATLANTIS II*) and St. 669 (*CHAIN*) was silicate, which was appreciably higher, by perhaps an order of magnitude, than that typical of surface waters in the tropical Atlantic. This persistence of high levels of silicate far out at sea was also found off the Columbia River by Stefánsson and Richards (1963); however, this is in direct contrast to the situation at the mouth of the Mississippi River, where Bien et al. (1958) found that this element was rapidly removed when the river outflow mixed with seawater, presumably in that case through inorganic precipitation.

As mentioned earlier, the regular hydrographic station data obtained on *CHAIN* 48 were supplemented by surface samples collected with a plastic bucket at one-hour intervals. To show the relationship between surface nutrient concentrations in the low-salinity pool and in the surrounding seawater, the hourly data have been plotted along a section across the region of minimum salinity between Sts. 674 and 666 (Fig. 4); this is shown as Section 2 in Fig. 2. Also shown are the surface phytoplanktonic cell counts obtained from hydrographic stations but not from the hourly bucket samples. The latter therefore show less detail, but they do show the same general trend as the nutrient data.

The low-salinity region in the center of the section is clearly revealed by the low density and, as mentioned above, its Amazonian origin indicated by the concurrent high values of silicate. However, neither the other nutrients nor the phytoplanktonic cell counts were significantly higher in this region, and there is even some suggestion that phosphate, at least, was somewhat lower than that outside the low-salinity water.

At the shoreward end of the section, on the other hand, phosphate, total phosphorus, and phytoplankton increased markedly. At first glance this might suggest terrigenous contributions from the South American continent, but an examination of the distribution of nutrients with depth shows that such is not the case. Fig. 5 illustrates such a profile of density and nitrate across the same section (Sts. 666–674) to a depth of 100 m. In Fig. 5 is also a profile of another similar section made during the fall cruise (*ATLANTIS II-14*), including Sts. 447,

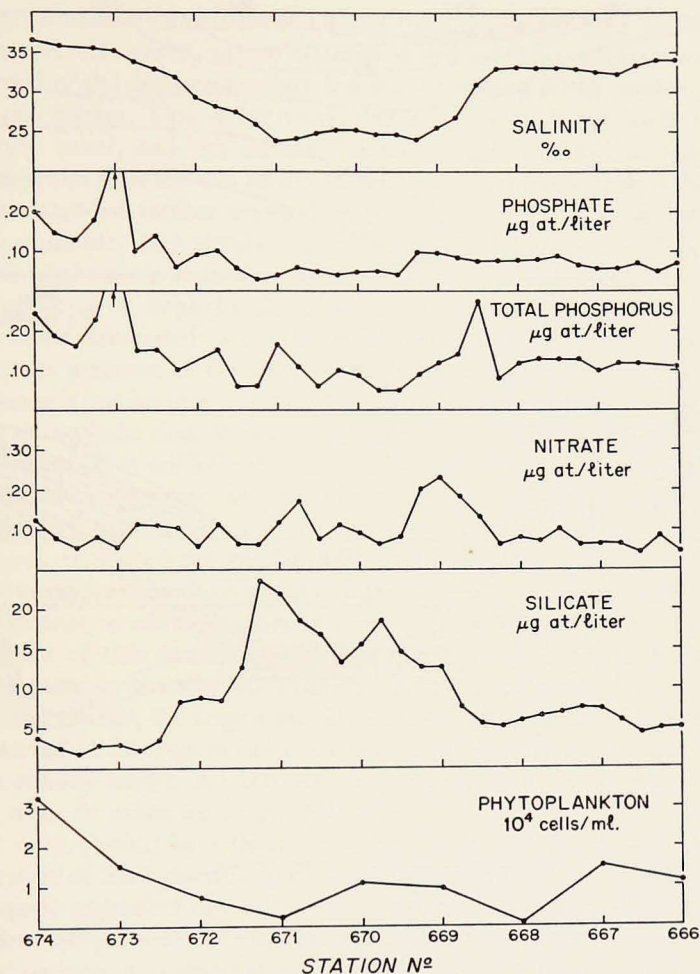


Figure 4. Surface chemistry determined from hourly bucket samples and phytoplankton cell counts taken at station positions along Section 2 (shown in Fig. 1) between Sts. 674 and 666 (May-June 1965).

448, 484, 492, 491, and 490. The latter is shown as Section 1 in Fig. 1. Nitrate is used as an index of nutrients in general, there being a simultaneous increase with depth in all those measured (NO_3^- , PO_4^{3-} , SiO_3^{2-}).

The profiles for both sections clearly show at their centers the pools of Amazon River water extending to a depth of 10–20 m. The surface density differences shown in the profiles were due almost entirely to salinity, the variations in temperature being very small (ca. 1°C), and the surface temperatures were actually higher at the seaward ends than in the center of the sections.

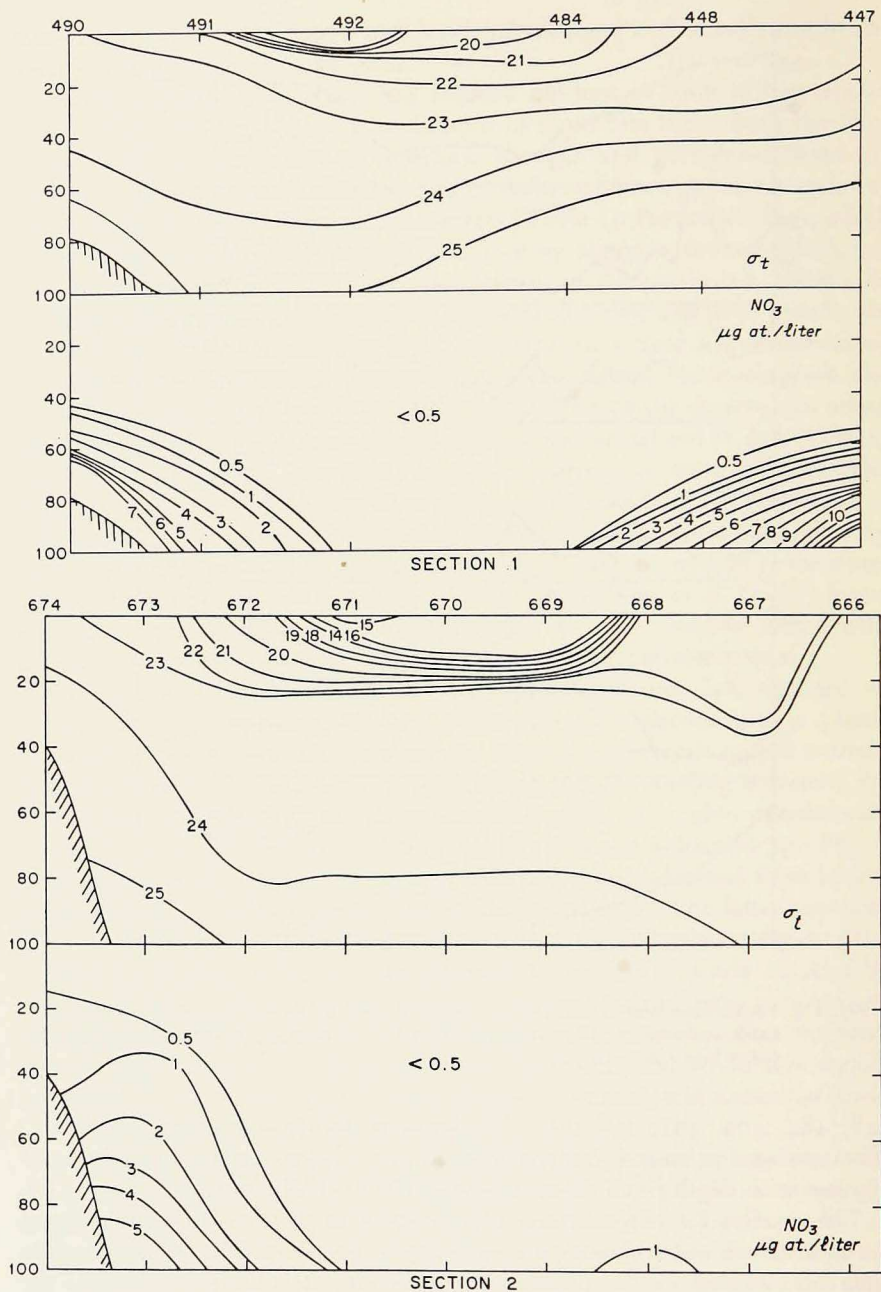


Figure 5. Density and nitrate profiles to 100 m depth along Sections 1 (November 1964) and 2 (May-June 1965) (see Fig. 1).

Again, no nutrient enrichment appears to be associated with the freshened surface water. However, at the shoreward end of both sections and at the seaward end of the fall section there is a sharp uptilting of the isopleths of both density and nitrate. The spring section shows a much larger surface pool of low-salinity water, and the density isopleths below this (i.e., σ_t 24) are still depressed at the seaward end of the section. It seems likely that if the section had been extended farther seaward in a northeasterly direction, an offshore uptilting of density and nitrate surfaces comparable to that found during the fall cruise might have been observed.

The uptilting of isopleths along the coast presumably represents the geostrophic slope associated with the swift Guiana Current (Defant 1961). Whether the presence of the fresh-water lenses enhance or contribute to this phenomenon is not known, but a causal relationship is suggested by the offshore uptilting of isopleths that do not appear to have any relationship to the coastal current system. It is unlikely that the fresh-water lenses are static phenomena. If, in fact, they represent anticyclonic eddies, an uptilting of water at their edges would be expected.

However, whatever the mechanism, it is clear that the sloping of water along the coast provides the enrichment in that region. As can be seen in Fig. 5, a rapid increase in nitrate occurs at depths below roughly the σ_t 24 surface. When water of this density is found in the euphotic layer, as in the water along the coast, it provides the stimulus for increased biological productivity. During both cruises, the largest planktonic populations, both plant and animal, were observed in this region (with the exception of those occurring within the Amazon estuary itself). An active shrimp fishery based in the Guiana's presumably owes its existence to this feature.

Lewis et al. (1962) have shown that low surface-salinity water invades the coastal waters of Barbados during the summer months (May-August), and they have properly attributed this to "waters from the rivers of the North coast of South America", as reference to Fig. 3 will confirm. They have also described a marked increase in zooplanktonic standing crops for the same time of year, an occurrence that coincides with the breeding season of the flying fish, the basis of the commercial fishing industry in Barbados. Calef and Grice (1967), have described the zooplankton collected during the two cruises discussed here; for the spring as compared with the fall, they have reported a three-fold over-all increase in population size observed in the entire region studied. It is tempting to relate these fluctuations directly to the river discharge and its seasonal variability. In the opinion of Vannucci and Queiroz (1963), "The influence of the mouth of the Amazon is felt many miles offshore to the north and northeast in the sense of contributing intensely to the addition of the standing stock of plankton, which is, without a doubt, due to the contribution of terrigenous material . . ." As noted above, however, the river water itself is conspicuously impoverished of nutrients and can hardly enhance directly

the biological productivity of the ocean into which it drains. Evidence has been presented by Calef and Grice (1967) that coastal zooplanktonic populations may be transported considerable distances seaward, but this is hardly adequate to explain the over-all increase in plankton in the region studied. It appears more likely that the main influence of the river water is indirect, by causing, or at least contributing to, the upwelling of nutrient-rich water at its periphery. The occurrence of such upwelling along the South American coast and within the swift Guiana Current insures the distribution of the enriched water over a large section of the eastern Caribbean and the western equatorial Atlantic.

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